

Environmental Waste Reuse in Geotechnics: A Review of Soil Stabilization through Pozzolanic Reactions

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ABSTRACT: The significant increase in industrial and agricultural waste has raised substantial environmental concerns, prompting the exploration of more sustainable methods for their reuse in geotechnical engineering. This review paper aims to investigate the potential use of bottom ash (BA), fly ash (FA), rice husk ash (RHA), coffee husk ash (CHA), sawdust ash (WSA), and granulated blast furnace slag (GGBS) to enhance the geotechnical properties of soil for various applications. The study results demonstrated the optimum replacement ratios for each additive, focusing on improving the mechanical and chemical properties of the soil. The improvements observed were mainly attributed to pozzolanic interactions. Specifically, the results included a 400% improvement in California bearing ratio (CBR) values at 20% BA content, a 35% increase in unconfined compressive strength (q_u) values at 30% GGBS, and a 57.4% decrease in soil plasticity at 20% CHA with 9% gypsum. Additionally, adding 15% of RHA raises the q_u value from 510 to 1100 kPa. Ultimately, this study supports the sustainable reuse of waste materials in soil stabilization, promoting their use in various engineering applications while reducing reliance on traditional, environmentally harmful stabilizers.

KEYWORDS: Geotechnical Engineering; Pozzolanic Interactions; Soil Stabilization; Soil; Environmental Concerns.

I. INTRODUCTION

The growing in population and industrialization have led to a significant increase in the amount of waste generated annually, causing concerns about their adverse impact on

the environment. The waste materials generated include concrete, gravel, ceramics, glass, wood, and other byproducts from building demolition, organic matter, cement, plastic, wood, and more. According to Figure 1, the amount of waste produced annually is increasing consistently, which was 2.017 billion in 2016, 2.586 billion in 2030, and 3.401 billion in 2050. Waste production differs across regions due to consumption rate, population growth, and economic growth. Developed countries generate high amounts of waste because of their high consumption style. Instead, developing countries produce a relatively smaller percentage of waste, so they face challenges in disposing of this waste. The increase in waste is a critical issue that poses challenges to health, the environment, and the economy [2] [54] [52] [50] [51]. It leads to pollution and depletion of natural resources. To fix this issue, scientists are focusing on developing solutions such as recycling, bio-analysis, promoting sustainable design and green manufacturing, and increasing the awareness of waste management. Civil engineers have an important role in waste management to promote environmental sustainability and reduce costs, as they reuse waste for construction applications (e.g., roads, pavement, concrete mixes, railroad, asphalt, etc.) Bolden et al.[27]; Mohajerani et al.[110]; Mohajerani et al.[109]; Rahman et al.[126]; Bamigboye et al.[19]; Reiterman et al.[130]; Nalon et al.[162]; Indraratna et al.[84]; Zaid and GÜNAL [156]; Eid et al.[41]. Hasim et al. [56] showed that replacing fine and coarse aggregates of concrete with 50%, 60%, 70%, 80%, 90%, and 100% of fine and coarse coal bottom ash decreased the value of concrete slump flow. The compressive and tensile strength of concrete reached a maximum value at 50% replacement of fine and coarse coal bottom ash.

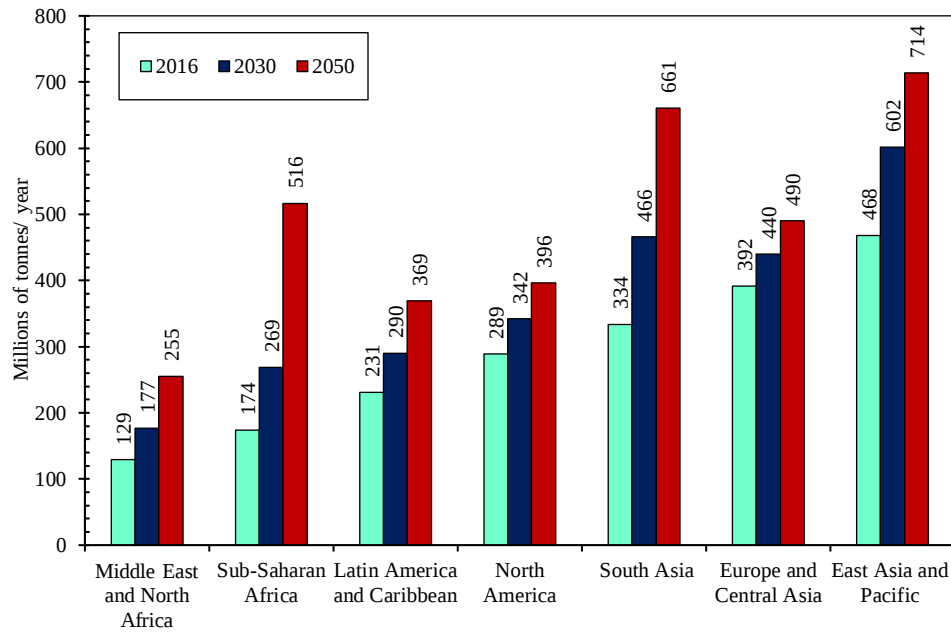


Figure 1: Projected waste generation, by region (millions of tons/years) (Kaza et al., 2024).

Meanwhile, researchers are exploring the fruitfulness of waste materials in geotechnical engineering, particularly in soil stabilization. Figure 2 provides a map of density visualization obtained through VOS viewer software for the countries that use waste materials most commonly for soil stabilization. The results are based on 1954 scientific research papers published between articles, books, and scientific conferences. The red color represents the total links and strength between these countries in the use of waste materials. Interestingly, there is a strong interconnection between the United States, Spain, United Kingdom, China, Australia, India, Thailand, Turkey, Italy, and Germany. Concurrently, there is a strong similarity and correlation between research conducted in Nigeria, Malaysia, Indonesia, Egypt, Iraq, Iran, Japan, Canada, and Taiwan.

Wherefore, geotechnical researchers have highlighted that waste materials can be effective in enhancing soil properties, such as bearing capacity, k , swelling, plasticity, specific gravity (G_s), CBR, q_u , and several mechanical and physical properties [5] [81] [34] [11][14] conducted a study on the effect of fly ash, rice husk ash, bagasse ash, and agricultural waste material rice straw ash (5 to 35%) in clay soil. The results showed a decrease in the maximum dry density of the clay, an increase in optimum moisture content, as well as an increase in CBR values. Besides, soil improvement can be achieved through physical, biological, and chemical techniques. Chemical methods, which use traditional materials like cement and lime or non-traditional materials such as polymers and enzymes, have proven to be more effective in improving soil properties.

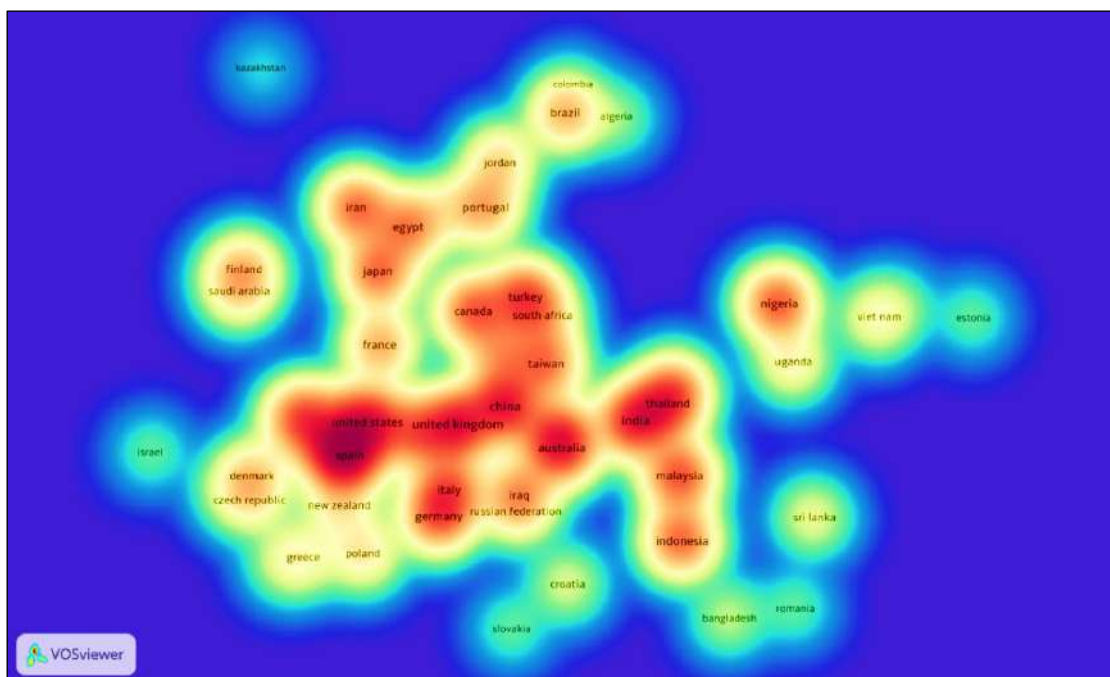


Figure 2: Density visualization map of countries that utilize waste material in soil stabilization.

The objective of this study is conducting a comprehensive review and analysis of various waste materials, including bottom-fly-ash, wood waste, ground granulated blast furnace slag, and husk ash, to assess their effectiveness in enhancing soil properties. Several researchers have demonstrated the potential of these materials in the field of geotechnical engineering, and their use has been proven to be beneficial in the construction of roads, pavements, and other structures. Moreover, their utilization can play a significant role in environmental conservation. This study highlights the importance of exploring the potential of these waste materials and their positive impact on the geotechnical field with constructive recommendations for researchers.

II. MATERIALS, RESULTS, AND DISCUSSION

A. Bottom and Fly Ash Wastes

Soil reinforcement using bottom ash is a technique employed to improve the mechanical properties of soil. Bottom ash, a by-product of coal combustion in power plants, has gained popularity as a construction material due to its unique properties, including high porosity, low density, and effective drainage capacity. Several studies have investigated the impact of bottom ash on soil reinforcement [48] [90] [157] [141]. Forteza et al. [49] presented findings indicating that the metal levels in raw bottom ash (BA) and its leachates comply with environmental regulations, provided that the ash is stored for at least one month. The engineering characteristics of BA resemble those of natural aggregates, suggesting that using these residuals in road construction is a practical option. Pant et al. [117] found that geogrid embedded in compacted BA exhibited similar resistance to that in the sand. In contrast, un-compacted fill material reduced pullout resistance by 30-60%. These results emphasize the importance of proper placement conditions for effective reinforcement. The addition of 0-50% BA to the soil, combined with lime content, enhances the development of the strength index and improves curing time, which ranges from 1 to 56 days. Generally, 50% BA with 12% lime resulted in a doubling of strength improvement and high

durability [24] [135] [71] [51] identified the optimal proportions of fly ash (FA), BA, and soil to enhance the strength of the mix. The study showed that a mixture consisting of 12% BA, 18% FA, and 70% soil improved the CBR value by 13.7%, representing a 4.02% increase compared to the original soil.

However, supplementary Table S1 provides the change in soil parameters that affect its properties and the potential its use in various applications. For example, Jorat et al. [92] showed that mixing kaolin soil with BA at 0, 25, 50, and 60% decreased the parameters of C , γ_{max} , and w_{opt} . Conversely, the ϕ increased. Notably, the CBR value showed a significant increase up to 50% BA. The pozzolanic nature of BA, which consists of silica, alumina, and unburned carbon, affects kaolin soil properties. The cohesion values decrease due to the disruption of the bonds between kaolin particles, which are replaced by coarser, less cohesive particles. Additionally, the high specific gravity and porosity of BA cause a decrease in density and moisture content. CBR values showed improvement at 50% BA content, attributed to the densification and rearrangement of particles, which enhances load-bearing capacity. Overall, the pozzolanic interactions between the silica and alumina in BA with calcium from the kaolin result in the formation of cementitious compounds, which may improve kaolin properties. However, a high BA content may lead to particle instability. Furthermore, Phan et al. [120] conducted a study on the impact of BA content on the pH and electrical conductivity of clay soil. The finding indicated that the addition of 5, 10, 20, and 30% of BA improved the pH values by 14, 21, 26, and 31%, respectively. In terms of electrical conductivity, the improvements were 208, 340, 491, and 655%. The observed improvement in pH values with the addition of BA is due to its alkaline nature. BA contains calcium and magnesium oxides, which can help release hydroxyl ions (OH^-) into the soil mixture. This neutralizes soil acidity and raises the pH. Similarly, the notable increase in electrical conductivity is a result of the dissolution of soluble salts, including sulfates, chlorides, and carbonates found in the BA. These ions enhance ionic strength, consequently boosting conductivity.

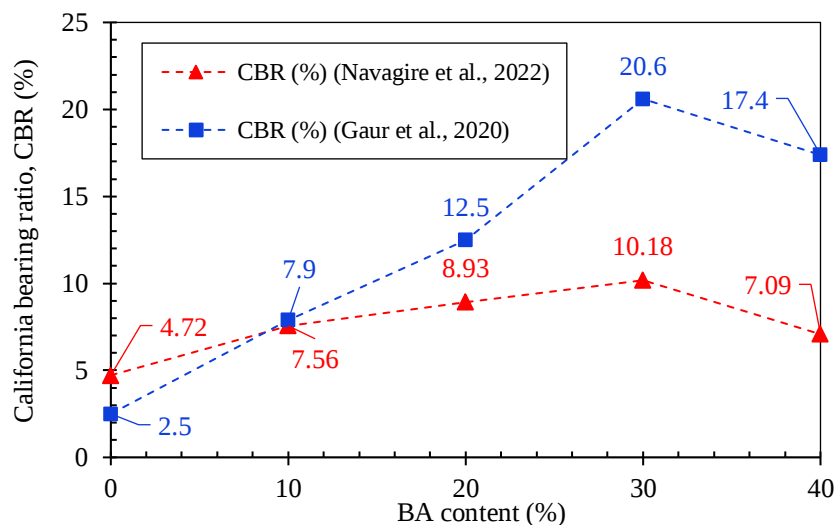


Figure 3: The CBR values of soil mixed with BA content.

Figure 3 summarizes the CBR values resulting from mixing 10, 20, 30 and 40% BA into BCS (Navagire et al., 2022) and clay soil [50][51]. The findings show a 216, 400, and 724% improvement in the CBR value of clay-BA mixtures at 10, 20, and 30% BA, respectively. In contrast, the BCS-BA mixtures showed an improvement of only 60, 89, and 116%. The greatest improvement in CBR of clay is attributed to the strong, highly malleable BA particles, which combined with the inclusion of coarser BA, these particles improve particle aggregation and reduce plasticity, thereby enhancing load-bearing capacity. Additionally, pozzolanic reactions between silica BA and alumina with calcium produce cementitious compounds that further enhance strength. BA has proven to be effective in soil improvement, particularly CBR values at specific concentrations, but its effectiveness decreases beyond a certain point, indicating a saturation point threshold. Additionally, the significant decreases in density and moisture content could negatively impact soil behavior and durability in various applications. It has also been noted that the pozzolanic reactions with BA are conditioned by the presence of lime, thus, its effectiveness when used alone is limited.

Fly ash is a fine, powdery byproduct of coal combustion, primarily composed of silica, alumina, and iron oxide. It has been widely used in geotechnical applications, particularly in stabilizing soil properties for greater usability. Its pozzolanic properties make it a cost-effective and more sustainable alternative to traditional stabilizers such as lime and cement, contributing to environmental conservation [121] [45]. Toth et al. [148] found that coal ash can be used as a substitute for natural materials in structural fields. Besides, in 2005, fly ash was utilized for highway embankments in Maryland. Brooks et al. [29] demonstrated that adding 0, 15, and 25% FA significantly improved the compaction and strength of clay soil. Their results indicated an increase in LL and PL values of clay, while the PI value decreased with the addition of FA. The $\gamma_{\max}$ value of clay decreased at all ratios of FA. This decrease can be attributed to the cation exchange process, the clay particles agglomerated with fly ash occupy larger areas, thus increasing the volume and reducing the density. Conversely, because FA absorbs water to complete the reaction, the w_{opt} of clay increased with the addition of 15 and 25% of FA. Furthermore, mixing 15 and 25% of FA with clay enhanced the soaked CBR values. The increase in CBR values can be attributed to cationic exchange, or flocculation in the mixture and agglomeration, which may form a cement gel resulting from the pozzolanic reaction of the clay-FA mixture. Similarly, the reaction of cationic exchange resulted in the replacement of the sodium ions with calcium ions, hence, reducing decreasing the swell values of mixture. The results also indicated that the q_u of clay decreased with FA addition, even after curing days of 1, 7, and 28 days. In simple words, this decrease is

explained by the fact that FA remained as a fine material when mixed with clay, leading to lower q_u values. Meanwhile, the CBR samples were soaked for 4 days in water, which allowed chemical reactions to occur between the clay and the FA, thereby improving the CBR values. Likewise, Turan et al. [149] showed improvements in the strength and CBR values of soil, a reduction in the PI value, prevention of soil swelling, and enhanced k values. The widespread availability, economic feasibility, and eco-friendliness of FA make it an attractive material for soil stabilization in geotechnical applications. These characteristics make FA a popular choice among researchers and practitioners in the field of soil stabilization. The effect of FA addition on the properties of clay, BCS, silty soil, sand, and other types of soil can be observed in Table S2. For instance, the LL value of clay decreased with addition of 3, 6, 9, and 12% FA. The 3 and 6% additions of FA reduced the $\gamma_{\max}$ and increased the w_{opt} . However, the q_u enhanced with the addition of 6% FA [23].

FA content has been applied to CL, OL, and MH soils to improve the CBR value [124]. Figure 17 presents a comparison between CBR values for soils mixed with 9, 20, 28.5, 35.5, 41.2, and 46% FA. The CL-FA mixtures show significant improvements in CBR values, with enhancements of 49, 88, 96, 111, 127, and 147%, respectively. Additionally, mixing FA with OL and MH soils also resulted in increased CBR values, as shown in Figure 4. The higher CBR values of CL soil can be attributed to pozzolanic reactions. CL rich in fine clay particles react more effectively with the calcium and silica in the BA, forming cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These compounds enhance soil cohesion and stability. In contrast, OL and MH soils have higher organic matter content and clay fractions, exhibit reduced pozzolanic reactions. The effect of 5, 10, 15, and 20% FA content on the $\gamma_{\max}$ values of clay (Sezer et al., 2006), BCS (Jujuri et al., 2025), and silty clay [96] are presented in Figure 5. The $\gamma_{\max}$ of clay and silty clay showed a clear decrease when mixed with FA. While the $\gamma_{\max}$ of BCS-FA mixtures increased, with improvement of 7, 35, and 36% observed at 5, 10, and 15% FA addition, respectively. The variation in density values in clay is affected by the physical properties of the FA. When FA content is added to clay, it often results to a decrease in $\gamma_{\max}$ because the FA particles tend to act as fillers. This reduces the efficiency of void filling, resulting in increased porosity and decreased $\gamma_{\max}$. In contrast, BCS shows improved $\gamma_{\max}$ behavior when mixed with FA. This enhancement is attributed to the presence of minerals such as montmorillonite, which exhibit greater interaction with the calcium and silica in the FA. This interaction promotes the formation of cementitious compounds, strengthening the soil particles, reducing voids, and ultimately increasing density.

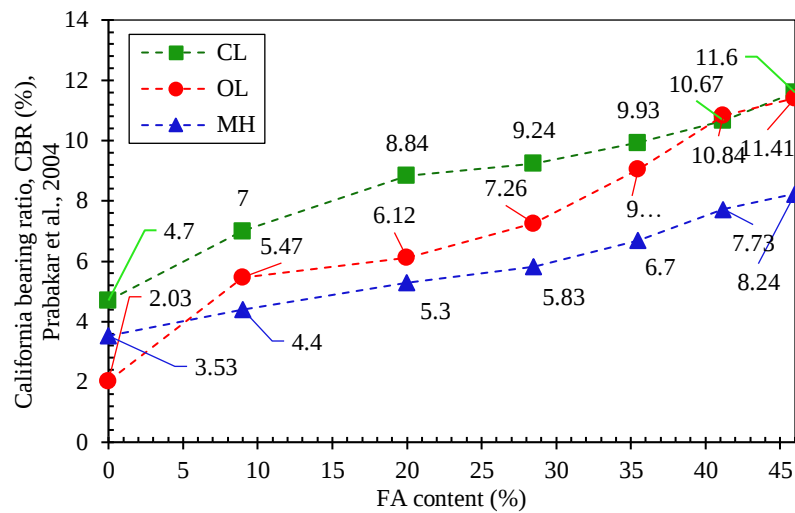


Figure 4: The CBR values of various soil types mixed with BA content.

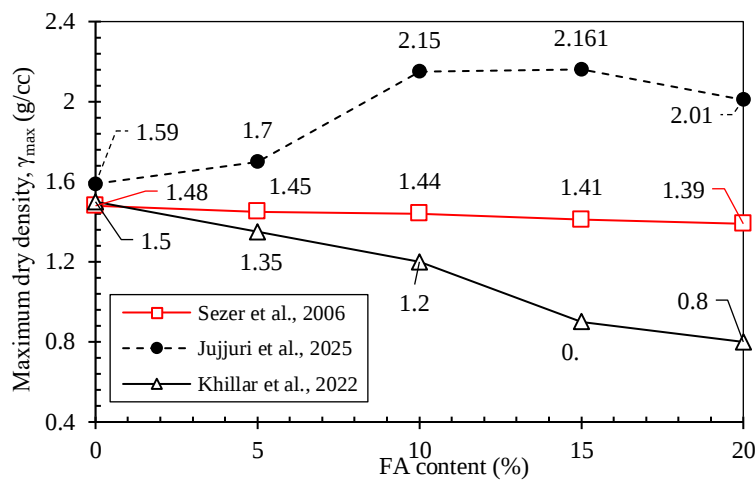


Figure 5: The $\gamma_{\max}$ values of various soil types mixed with FA content.

B. Husk Ash Waste

Rice husk is abundantly available in rice-producing countries such as Indonesia, Thailand, and the Philippines [60]. The practice of burning rice husk for parboiling paddy in rice mills often leads to partial combustion and environmental issues. To address these challenges, efforts are being made to utilize rice husk as a value-added substitute or auxiliary material for geotechnical and soil stabilization applications (Muntohar et al., 2013). Several researchers have investigated the use of husk ash (e.g., rice ash, coffee ash, and ground-nut ash) for soil improvement (Brooks et al., 2009; Akinyele et al., 2015; Behak et al., 2017; [124] [127] [131] [119] [143]. For example, Nnochiri et al. [160] found that $\gamma_{\max}$ of soil decreased from 19.22 to 17.26 kN/m³ at 10% ground-nut husk ash (GHA), while w_{opt} increased from 12.70 to 14.95%. The unsoaked CBR values of soil increased from 24.42 to 72.88%, and UCS values increased from 510.25 to 1186.46 kPa, with the highest values observed at 10% GHA. GHA can therefore be considered a cost-effective stabilizing agent for subgrade and sub-base applications in road construction. Ali et al. (1992) investigated the effects of 6, 12, and 18% of rice husk ash (RHA) on the silt clay properties. The results showed that increasing RHA content led to a reduction in $\gamma_{\max}$ of soil, decreasing from 1.6 to 1.47 g/cm³, while the

w_{opt} increased from 18.3 to 23.4%. The increase in $\gamma_{\max}$ and decrease in w_{opt} values is attributed to the properties of RHA, which has a low G_s value and high additional water properties. The q_u value of soil increased with addition of 12% RHA content but then decreased with longer curing time. Adding lime to the soil increases the pozzolanic interactions between silica from the soil and the lime, thus forming strong stabilizing agents. When RHA is added to the soil -lime mixture, the amount of silica increases to interact with lime, leading to enhanced bonding and strength. The optimal RHA content also improves the saturation resistance of soil. Therefore, treatment of residual soil with RHA-lime mixtures is beneficial for road construction. Various researchers have tended to use additional materials with RHA content to stabilize properties of soil, for instance, Basha et al., [21] investigated the effect of using 5, 10, 15, and 20% RHA in combination with 2, 4, 8, and 12% cement to stabilize RS. The results showed an increase in LL and PL values, a decrease in PI, and $\gamma_{\max}$ values, but an increase in w_{opt} of RS. The reduction in PI values signifies an improvement in the soil mixture, while the decrease in $\gamma_{\max}$ values suggest enhanced resistance within the soil structure against external forces during practices. The q_u value increased with the addition of 5% RHA to the soil but then decreased.

Conversely, the addition of 4 and 8% cement to RHA increased the UCS of RS. The CBR value decreased with higher RHA content, but adding RHA to cement-treated soil improved CBR values. The optimum amounts for improvement were found to be 6-8% cement and 15-20% RHA. Overall, RHA has demonstrated significant potential for soil stabilization and is a cost-effective option, particularly in rural areas of developing countries. Liu et al. [105] found that increasing the content of RHA content and calcium carbide residue (CCR) significantly reduced the number of cracks in ES, as shown in Figure 6. At 0% of additives, there were more than 30 coarse cracks. When the additive increased to 5%, more than 20 cracks were observed, with half being coarse. At 10% addition, there were approximately 10 cracks, a few of which were coarse. When the blending content was increased to 15%, more than 5 visible but mostly thin cracks were observed, while at 20%, there were less than 5 mostly thin cracks. Additionally, the RHA-CCR also improved the q_u , C, and ϕ values of the soil. The maximum C value enhanced by 2.45 times compared to uncured soil with the addition of 15% RHA after 28 days of curing. Similarly, the ϕ value improved by 2.43 times with a 15% addition of RHA after 90 days of curing compared to uncured soil. Furthermore, Table S3 summarizes the use of RHA in different soil types, such as silty, clay, and organic soil. The results indicate a

significant change in soil structure due to the varying reactions between soil particles at various ratios of RHA, making it more suitable for use in geotechnical applications. For example, Alhassan [9] studied the effect of adding 2, 4, 6, 8, and 10% RHA into clay soil. The outcomes of this study revealed an increase in w_{opt} and CBR values, while the γ_{max} decreased. Additionally, the q_u improved up to 8% RHA, even with extended curing time. The addition of RHA to clay causes changes in its structure. Generally, RHA contains significant amounts of silica, which interacts with the aluminous components in the clay to create strong cementitious compounds. This reaction enhances the structure and strength of the clay, and these improvements continue to inverse with curing. Additionally, the low Gs of RHA contributes to decreased γ_{max} values, while its high-water absorption increases the w_{opt} value.



Figure 6: Crack morphology of ES with RHA-CCR content (curing time = 28 days) (Liu et al., 2019).

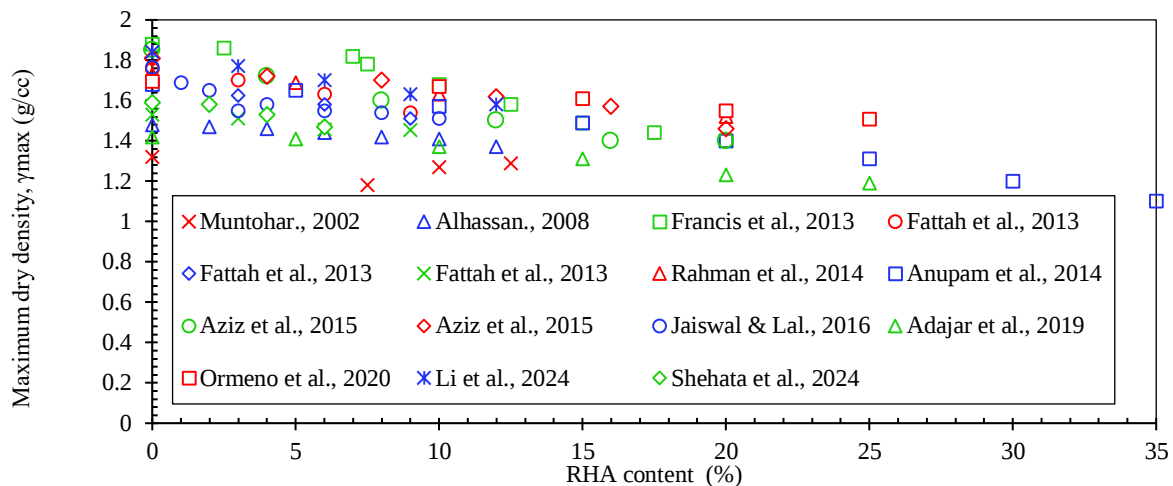


Figure 7: The effect of RHA on γ_{max} of soil.

The effect of RHA content on γ_{max} values of various soil types, such as high plasticity clay, low plasticity clay, silty clay, red coffee soil, and others, is presented in Figure 7. The general trend for all values showed a decrease at RHA ratios between 0-35%. This decrease can be attributed to properties of RHA, which has lower Gs than soil. Specific gravity measures a material's density relative to the density of water. Since RHA has a lower specific gravity than soil, it weighs less and can be absorbed between soil particles, reducing the overall γ_{max} of the mixture. Chemically, incorporating RHA into clay does not change its chemical composition, but it does alter its physical properties related to density. This reduction in density also generally affects the compressive behavior of the soil. Lighter particles result in less compressible materials compared to denser soil, affecting the soil's strength and load-bearing capacity. Figure 8 illustrates the decrease in the w_{opt} of soil mixed with 0-35% of RHA. Generally, RHA has a high-water

absorption capacity due to its porosity and large surface area. These properties enable greater water absorption when mixed with soil. Chemically, RHA contains silica, so when added to soil, it forms a network of microscopic pores that trap water. Its high surface area allows for greater moisture retention, leading to higher w_{opt} values for the mixture. Figure 9 presents the γ_{max} results for CH [47], OL [18], and CL [88] mixed with 0-20% RHA. The results indicate that the CH-RHA mixtures exhibited the highest γ_{max} values, showing decrease s of 3.2, 6, 10.5, 13, and 19% at 4, 8, 12, 16, and 20% RHA, respectively. The OL-RHA mixtures showed the second highest γ_{max} values, with a clear decrease of 4, 6.5, 12, 10, 12, 13, and 14% at 1, 2, 3, 4, 6, 8, and 10% RHA, respectively. In contrast, the γ_{max} values for CL-RHA mixtures were the lowest. This variation in density can be explained by pozzolanic interactions between the silica in the RHA and the ammonia in the clay, which allows strong pozzolanic interactions.

These interactions are particularly strong in CH, resulting in higher densities compared to organic soils, which contain lower amounts of ammonia. Additionally, CL also exhibits lower densities because they contain lower amounts of both silica and ammonia. However, the w_{opt} of CL mixed with 3, 6, and 9% RHA showed the highest improvement of 5, 12, and 16%, respectively, as shown in Figure 10. For CH, the w_{opt} values were the lowest among the soil types, showing improvement of 8, 15, 23, 35, and 40% at 4, 8, 16, 18, and 20% RHA, respectively. In OL, the w_{opt} values clearly improved by 50, 77, 95, 100, 109, 109, and 118%, at 1, 2, 3, 4, 6, 8, and 10% RHA, respectively. The CL has a finer grain structure with larger particles, which creates

greater water-holding capacity, resulting in higher water content values when mixed with RHA. In contrast, CH contains finer particles that bond more tightly with RHA, reducing the water required for compaction. In other words, CL require more water to reach optimum strength than CH. Figure 11 demonstrates the CBR values of CH [129], OL [88], and CL [113] when mixed with RHA. The highest CBR values were noticed in CL-RHA mixtures, with values of 4.3, 15.4, 18.9, 20.7, and 23.7% at 10, 15, 20, and 25% RHA, respectively. The CBR values of OL-RHA mixtures were recorded 7.1, 7.7, 9.4, 9.2, and 10.1%, respectively. Additionally, the CBR of CH mixed with 10, 20, 30, 50, and 80% RHA were the lowest compared to those of CL and OL, as shown in Figure 11.

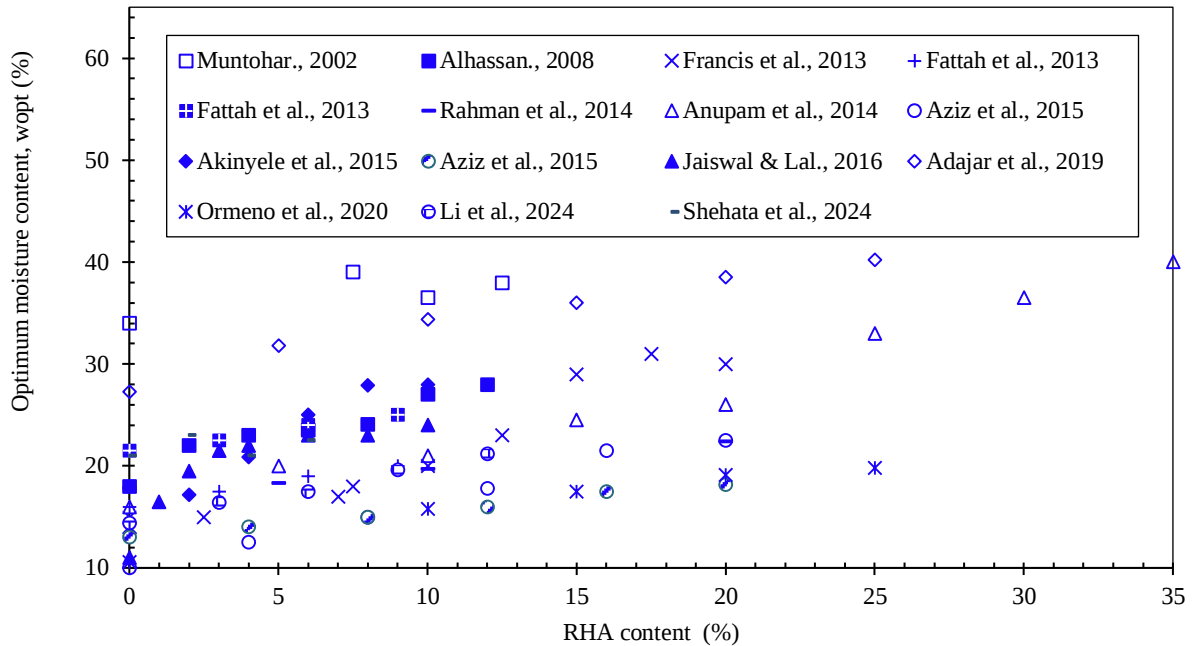


Figure 8: The effect of RHA on w_{opt} of soil.

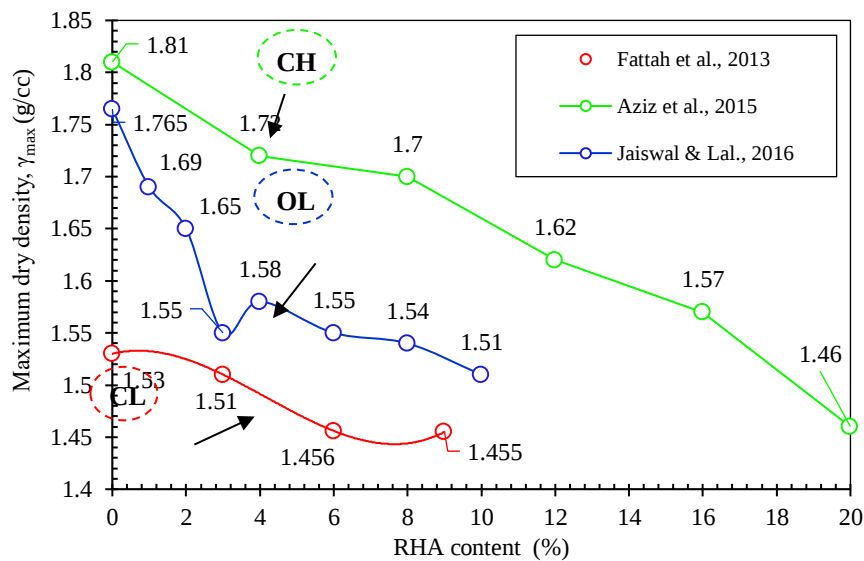


Figure 9: The effect of RHA on γ_{max} of high and low plasticity clay and organic soil.

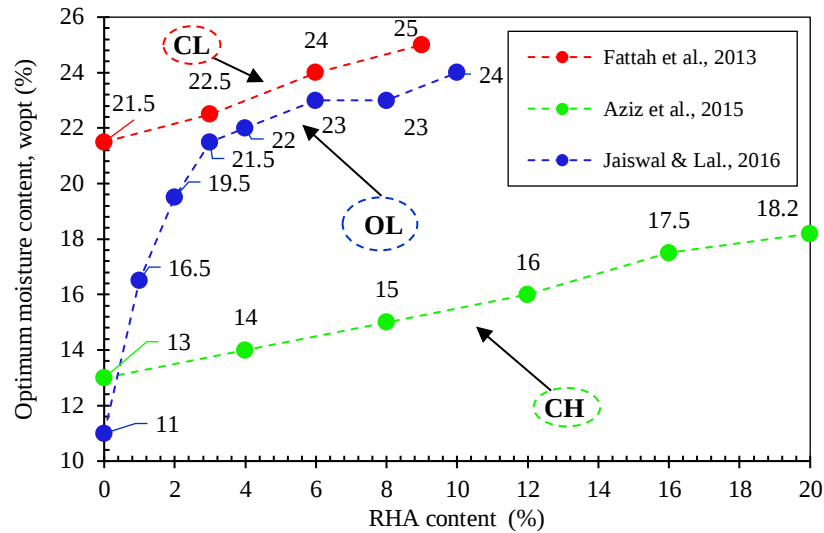


Figure 10: The effect of RHA on w_{opt} of high and low plasticity clay and organic soil.

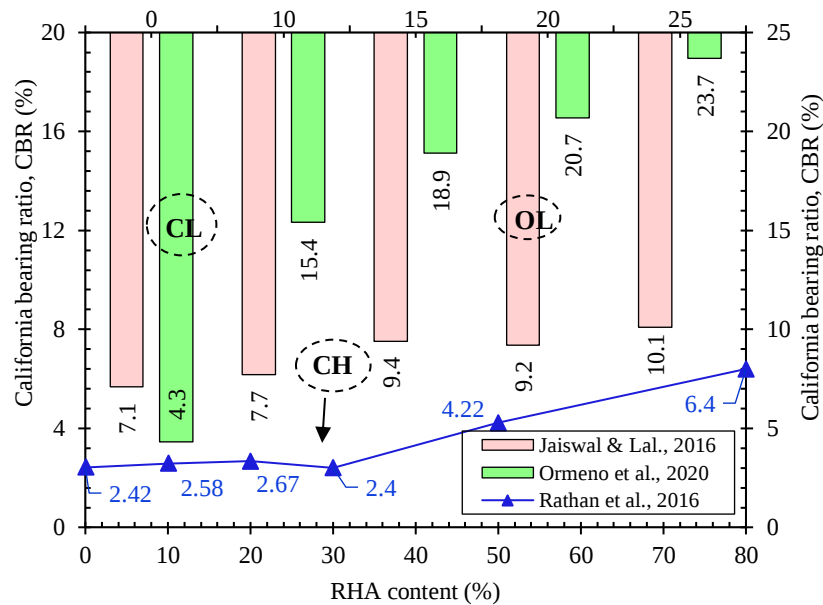
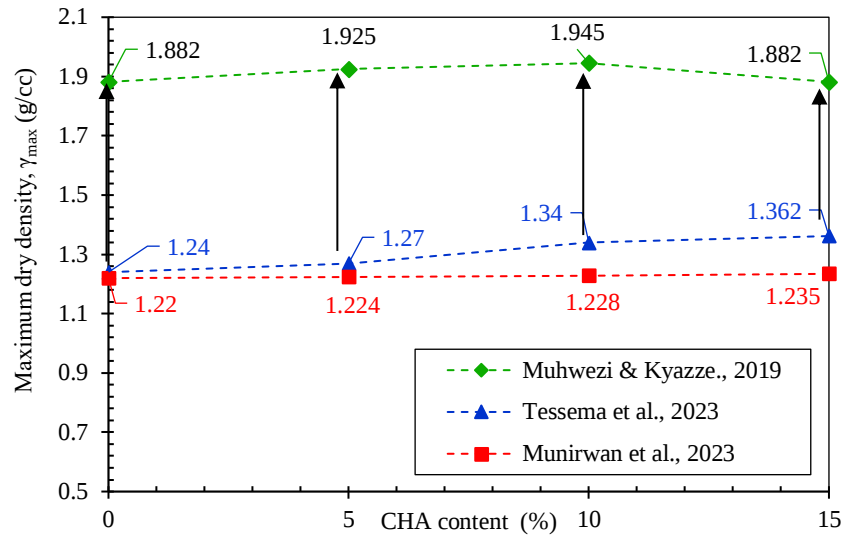


Figure 11: The effect of RHA on CBR of high and low plasticity clay and organic soil.

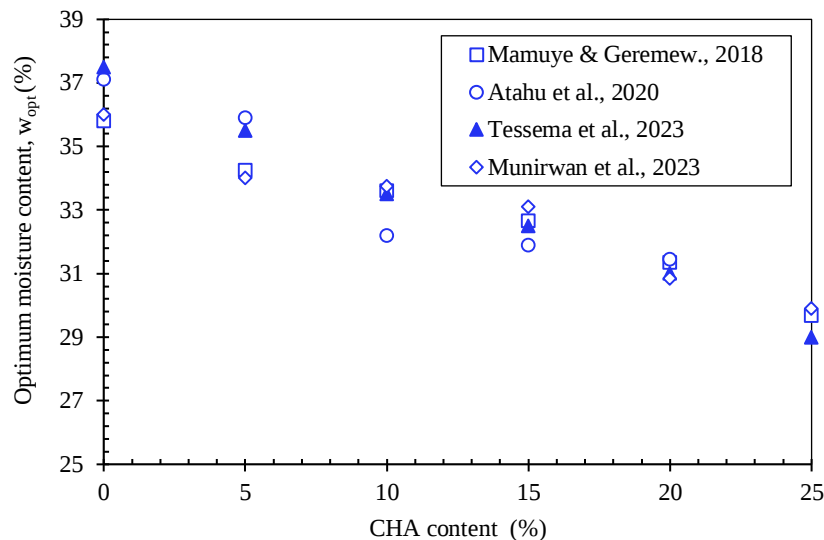
Some researchers have explored soil stabilization using coffee husk ash (CHA). It has been found to contain alumina components that help improve soil through pozzolanic bonds. CHA has higher levels of potassium and other minerals, such as magnesium, phosphorus, and trace minerals like iron and manganese. These components can affect soil properties differently than RHA. Table S4 presents the characteristics of various soil types mixed with CHA. For instance, Munirwan et al. (2023) studied the influence of 5, 10, 15, 20, and 25% of CHA on properties of clay particles. The results showed a decrease in LL, PI values which reduce the swelling of soil [125], while the PL values of all clay-CHA minutes increased. The γ_{max} values improved with addition of CHA (5-25%) to the clay soil due to high Gs of CHA, which reflects the enhanced in the clay particles gradation with CHA content. Meanwhile, the w_{opt}

values of the clay - CHA mixtures decreased, which can be attributed to low absorption of water for CHA content in clay soil. Figure 12 shows the general increase in γ_{max} values of different soil types mixed with CHA. The γ_{max} values in CH have increased from 1.22 g/cc to 1.224, 1.228, and 1.235 g/cc (Munirwan et al., 2023) and from 1.24 g/cc to 1.27, 1.34, and 1.362 g/cc [146] when mixed with 5, 10, and 15% CHA, respectively. Although the γ_{max} values are somewhat comparable, the difference can be attributed to a slight difference in the size of the particles used in each study. Notably, the highest γ_{max} values were recorded in gravel-CHA mixtures, as shown in Figure 13. The improvements observed were approximately 51, 57, 58, and 34%. Overall, this improvement in γ_{max} values is due to the pozzolanic reactions between the particles and the Gs value of CHA.

Figure 12: The effect of CHA on $\gamma_{\max}$ of soil.

The w_{opt} of different soil types mixed with CHA is illustrated in Figure 13. The results showed a clear decrease in w_{opt} for all mixtures. This significant reduction can be attributed to the low water absorption properties of CHA. Consequently, substituting soil particles that effectively absorb water with less absorbent particles results in a decrease in their w_{opt} . Furthermore, [145] stabilized the ES by adding CHA in ratios of 5, 10, 15 and 20%. The results revealed a decrease in the LL, PL, and PI values, which contributed to an increase in the strength of the soil mixture due to reduction in the PI. By mixing the soil particles with

CHA content, the $\gamma_{\max}$ values of mixtures increased by up to 15% CHA addition, as the CHA filled the voids between particles with its high Gs, promoting the agglomeration and flocculation of clay- CHA particles as a result of quick cation exchange. In contrast, the w_{opt} values decreased across all CHA ratios due to low absorption water of stabilizer. The addition of CHA also reduced the swelling of ES, as more CHA was introduced, it formed a better agglomeration and decreased the soil's volume change. Consequently, the CBR value of the soil increased with CHA content.

Figure 13: The effect of CHA on w_{opt} of soil.

Some researchers have tended to mix CHA with other additives into soil to enhance their mechanical and chemical properties. For example, Tessema et al. [146] studied the effect of mixing 5, 10, 15, 20, and 25% of CHA with 3, 6, and 9% of gypsum on clay properties. The results of their study showed that mixing clay soil with 20% CHA content decreased the LL and PI values by 24.5 and 57.4%, respectively. Similarly, when 9% gypsum was added to a clay-15% CHA mixture, the LL and PI values decreased by 41.5 and 81.5%, respectively. A decrease in PI values is a good indicator of a reduced swelling in the clay. The $\gamma_{\max}$

values of clay- CHA mixture increased, while the w_{opt} values decreased. In contrast with the addition of 9% gypsum to the clay – 15% CHA the $\gamma_{\max}$ value decreased by 3.23%, and w_{opt} value increased by 11.60%. The CBR value of clay also increased with addition of CHA, especially when mixed with gypsum content, making it suitable for subgrade layers. The q_u value of clay increased when mixed with 5-15% of CHA. The highest value of q_u was at 15% CHA and 6% gypsum. This increase can be attributed to the additives that produce cement chemicals

that increase reactivity and hardening. Sreedevi et al. (2024) observed that q_u value of clay increased when mixed with 5, 10, 15, 20% of CHA, but it decreased with addition of 25% CHA. Furthermore, by adding 6% lime to clay mixed with 20% CHA, the q_u values significantly increased, reaching approximately 3.64, 3.68, and 3.75 kPa at 7, 14, and 28 curing days, respectively.

C. Wood Waste

Wood waste, including wood chips, sawdust, and bark mulch, consists of organic materials derived from trees and various wood processing and disposal activities. These activities occur in forests, wood mills, carpentry and furniture classification, and construction and demolition demolition sites. Wood waste contributes to soil improvement, addresses significant environmental concerns, enhances nutrient levels, increases water retention, and promotes microbial activity [115] [142] [89] [107]. Before using wood ash for soil stabilization, it may need to undergo certain preparation processes. This often includes screening to remove large particles and impurities. In some cases, wood ash is burned at high temperatures to eliminate unburned organic matter, which enhances its pozzolanic properties and makes it more effective at stabilizing soil. Sometimes, wood is mixed with other stabilizers such as lime or cement to enhance its bonding properties. For Insurance, Nnochiri et al. [161] demonstrated the impact of wood sawdust ash (WSA)-lime mixtures on q_u , γ_{max} , and w_{opt} values of lateritic soil (LS). It was observed that the γ_{max} value of the soil decreased with the addition of 2, 4, 6, 8, and 10% WSA- lime mixture. This decrease can be due to the mixing soil with WSA- lime that has a lower specific gravity, as well as the way the WSA-lime surrounds and covers the soil, introducing larger grain sizes that create significant voids within the soil, resulting in decrease in density. Conversely, the increase in w_{opt} value of soil with WSA- lime additions is due to the reduction in the amount of silt, clay fractions, and coarse materials with a large surface area, as these materials require more water. Furthermore, the q_u of soil increased from 38.58 kPa to 129.63 kPa with an addition of 6% WSA-lime. This increase can be explained by the formation of cementitious compounds between $Ca(OH)_2$ present in the soil and the pozzolans found in SA-lime [12]. Mohamed et al. (2023) found that adding 1% cement along with 10% high calcium FA-WSA resulted in significant improvements in the strength of expansive soil. Additionally, Ingabire et al. [85] found that incorporating 6% WSA and 9% rice husk improved q_u , CBR, and compaction parameters of BCS. These modifications increase their suitability as a foundation material for construction. Numerous studies have highlighted the importance of using WSA to stabilize various soil types. For instance, Ojuri et al. [111] showed that adding 5% of WSA increased the CBR value of soil from 41 to 57%. Additionally, when 10% SA was applied, the CBR value further improved from 58 to 79%. This indicates that WSA is an effective soil amendment for enhancing the load-bearing capacity of soil. Abdulwahab et al. [2] noted that the inclusion of 10% WSA in the soil had significant effects. It increased the w_{opt} of the soil, decreased the γ_{max} value, and significantly improved the CBR value by 46.72%. Furthermore, Table S5 presents the results of experiments conducted on clay, organic, and silty, and

sandy soils that were mixed with various proportions of WSA. The findings indicate that these mixtures positively stabilized affects the parameters of the stabilized soil, making it more friendly and suitable for engineering applications. Nath et al. (2018) investigated the effects of adding various percentages (5, 7.5, 10, and 12.5%) of WSA to the low plasticity clay. The results indicated a reduction in both the PI and γ_{max} values. WSA provided optimal values for the q_u , ϕ , w_{opt} , LL, and PL of the soil. Additionally, WSA was shown to decrease the compression index (Cc) while increasing the void ratio (e_0). The addition of WSA influenced the behavior of the soil through various interactions among the particles. WSA contains significant amounts of silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which contribute to pozzolanic reactions with clay minerals. Calcium oxide reacts to form calcium hydroxide ($Ca(OH)_2$), which then interacts with the silica and alumina to create effective cementitious compounds. These compounds bond with clay particles, reducing the PI by limiting particle mobility. Increased void content arises from insufficient interaction between the WSA and clay particles, leading to more bulged structure. The decreased Cc can be attributed to improved bonding between the clay and WSA particles, resulting in a more stable mixture. Figure 14 summarizes the q_u values of lateritic soil (LS) mixed with various ratios of WSA. The results were influenced by the size of WSA used: Group A consisted of WSA passing through sieve N.200 (Ogunribido et al. [163], 2012; Edeh et al. [40], while Group B included WSA passing through sieve N.40 [83]. For Group A, the addition of 2, 4, 6, 8, and 10% WSA decreased the q_u value of LS. When LS mixed with 10, 20, and 30% WSA, the q_u value increased with improvement of 28, 220, and 533%, respectively. However, at ratios of 40, 50, 60, 70, 80, and 90% WSA, the q_u began to decline. For LS mixed WSA (group B), improvement of 224, 211, 157, and 172% were observed at 8, 12, 16, and 20% WSA, respectively. Fine WSA particles (Group A) possess a higher surface area, which enhances their ability to engage in effective pozzolanic interactions with clay minerals, leading to formation of valuable cementitious compounds. When WSA content decreases to 2-10%, these interactions become incomplete, resulting in increased voids that weaken the clay structure and reduce deformation. However, at optimal WSA levels of 10-30%, sufficient pozzolanic bonding occurs, promoting the interlocking of particles and increasing their q_u values. When WSA content exceeds 40%, excess WSA disrupts particle cohesion. In contrast, coarser WSA particles (Group B) function as fine aggregates, improving the clay structure through mechanical interlocking rather than chemical bonding. Strength improves at 8-20% WSA content due to increased compaction and interlocking. The CBR values of clay soil mixed with WSA are presented in Figure 15. The CBR values of clay mixed with fine WSA showed improvements of 26, 43, and 51% at 2, 4, and 6% WSA, respectively. In sandy clay, the CBR values showed improvements of 5 and 27% at 4 and 6% WSA, respectively. However, both studies indicated a decline in CBR with an 8% addition of WSA. Suresh et al. (2023) demonstrated that incorporating 10, 20, 30, and 40% of WSA led to a decrease the γ_{max} value of bentonite. This reduction can be attributed to the flocculation and agglomeration of the bentonite molecules caused by the exchange process of exchange with the Ca^{2+} ion present in

WSA. As a result, the void spaces between the molecules increased, leading to a which reduction in density. The decrease may also be explained by the lower G_s of WSA. The w_{opt} value increased with the addition of 10% WSA but then decreased with higher percentages. The q_u value of bentonite increased to 113, 117, and 139 kPa with the addition of 10, 20, and 30% WSA, respectively, then decreased with 40% WSA. The q_u value continued to

increase over time due to the pozzolanic reactions. Furthermore, the CBR value of bentonite under soaked condition increased from 1.83 to 7.3% with addition of 24% WSA. According to the Indian Roads Congress (IRC., 2018), the CBR value should be greater than 5% for roads that accommodate 450 commercial vehicles daily. Therefore, the CBR value of bentonite mixed with 24% WSA is suitable for use as a pavement subgrade.

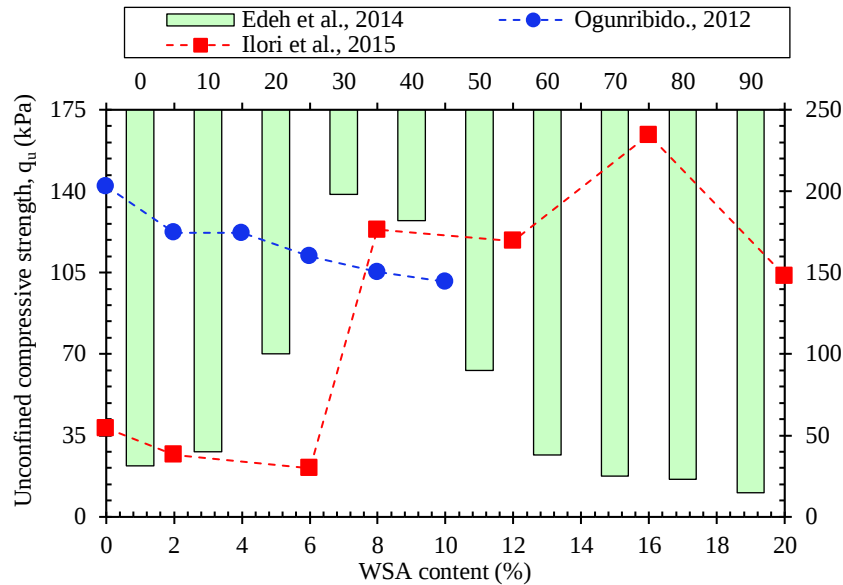


Figure 14: The q_u values of LS mixed with WSA content.

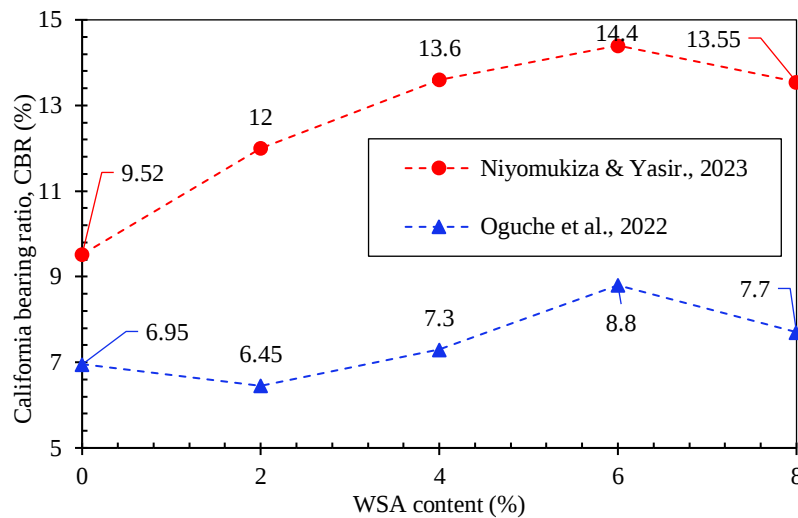


Figure 15: The CBR values of clay soil mixed with WSA content.

D. Ground Granulated Blast Furnace Slag Waste

Ground granulated blast furnace slag (GGBS) is a byproduct of blast furnace ironmaking. It is known for its low energy consumption and CO_2 emissions [53]. The effectiveness of GGBS in soil stabilization is well documented, and its use can help mitigate environmental issues related to waste disposal [59] [35] [118] [133] [55] [122] [1]. The utilization of GGBS can also reduce the carbon footprint and promote sustainability [153] [147]. Table S6 concludes the values of soil parameters affected by the addition of 1-100% GGBS. For example, Mujtaba et al. (2018) conducted a comprehensive study on CH and CL

soil mixed with 5-50% GGBS. The results showed that at 50% GGBS, both samples (CH and CL) showed an increase in γ_{max} values and CBR (up to 11.5% for CH and up to 10.7% for CL). Furthermore, there was a decrease in swelling potential (down to 2%) and a reduction in the w_{opt} . Additionally, the q_u value increased by 35% with the addition of 30% GGBS after 28 days of curing. GGBS is a stabilizer that creates effective cementitious compounds due to its silicate and aluminosilicate content. These components play a crucial role in the pozzolanic reaction, forming calcium C-S-H and C-A-H. This process enhances the soil structure, resulting in an increase in the γ_{max} (also

due to high Gs value of GGBS) and CBR of the mixture. However, GGBS is characterized by its high-water absorption, which reduces the w_{opt} of the clay and reduces the swelling potential. The increase in q_u values is attributed to the reinforcement of the soil matrix by gel-forming materials. This contributes to improved soil cohesion and resistance to deformation. However, the results consistently showed that all values of CH were higher than those of CL results. This can be attributed to the well-known chemical composition of high-plasticity clay, which contains the highest expansive clay minerals such as montmorillonite. Montmorillonite has a high-water absorption and swelling capacity. Additionally, it also has a larger surface area and ion exchange capacity, allowing for increased chemical reactions with the GGBS stabilizer.

Yunus et al. [155] studied the effect of GGBS on peat soil. The outcomes indicated that the γ_{max} increased by 0.6, 19, 22, and 32.5% at 5, 15, 25, and 50% GGBS, respectively. In contrast, the w_{opt} showed a decrease at the same ratios of GGBS. The q_u value improved by 160, 248, 220, and 80%, respectively, with the highest value observed at 15% GGBS. Likewise, Havanagi et al. (2024) incorporated 5, 10, 15, 20, 25, and 30% GGBS into BCS. The results showed a clear decrease in the w_{opt} , LL, PL, and PI values, while there was an increase in the γ_{max} , CBR, and UCS values. The common trend in the q_u values was an increase in most soil type that mixed with GGBS content, as shown in Figure 16. Besides, the highest UCS values were achieved in clay soil compared to silt, peat, and bentonite soil. The significant improvement in q_u of clayey soils compared to other soils can be attributed to their mineral properties. These properties allow for a distinct interaction with the GGBS and the formation of strong cementitious compounds that reinforce the clay matrix. For instance, while bentonite contains montmorillonite, its different swelling properties hinder its ability to interact adequately with the GGBS,

resulting in less reinforcement compared to clay. Furthermore, the inclusion of GGBS resulted in a decrease in the LL and PI values of various soil types, as illustrated in Figure 17 and 18. This reduction is attributed to the pozzolanic reaction, in which gels form and bind the soil particles together. This binding effect reduces the soil's plasticity and ability to absorb water, which is evident in the decrease in the liquid limit and plasticity index.

On the other hand, some studies investigate the effects of mixing GGBS with other stabilizers in soil. For example, Wild (1998) found that GGBS can effectively replace lime in stabilizing clay soils, particularly when combined with gypsum. The study suggests that 1.5 GGBS /lime yields the maximum strength for higher stabilizer contents, indicating the potential of GGBS as a binder for soil stabilization in foundation layers for structures such as highways. Yi et al. [154] conducted a study on the utilization of alkali activated and GGBS to stabilize marine soft clay. Their findings suggest that Na_2SO_4 -clay-GGBS exhibited superior binding properties, resulting in a strength increase of at least double in comparison to that of Portland cement stabilized clay. Fasihnikoutalab et al. [46] demonstrated that after 90 days, the soil treated with 20% GGBS showed a 142 kPa increase in q_u value. Additionally, the addition of 20% olivine increased the q_u value to 444 kPa, and the incorporation of 20% NaOH into the olivine-GGBS-treated soil resulted in a q_u value exceeding 6000 kPa in 90 days. These results demonstrate the effectiveness of GGBS in stabilizing soil properties, such as strength, plasticity, and compressive strength, making it an effective binder for construction materials, including highways and foundation layers. Additionally, its environmental benefits, which include reducing the need for traditional stabilizers like lime and cement, contribute to sustainability through utilizing an industrial byproduct and decreasing the carbon footprint of construction.

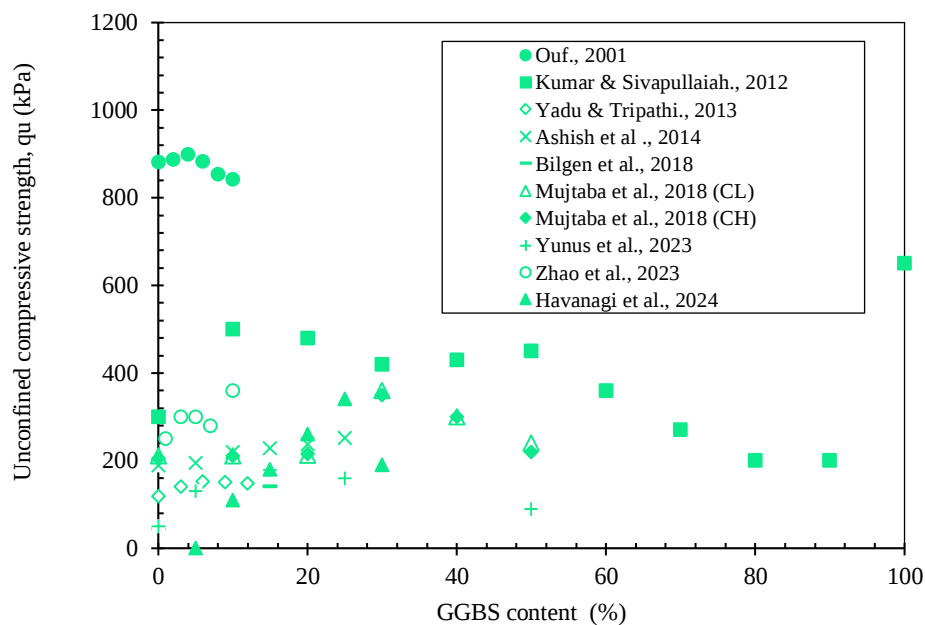


Figure 16: The effect of GGBS on q_u of soil.

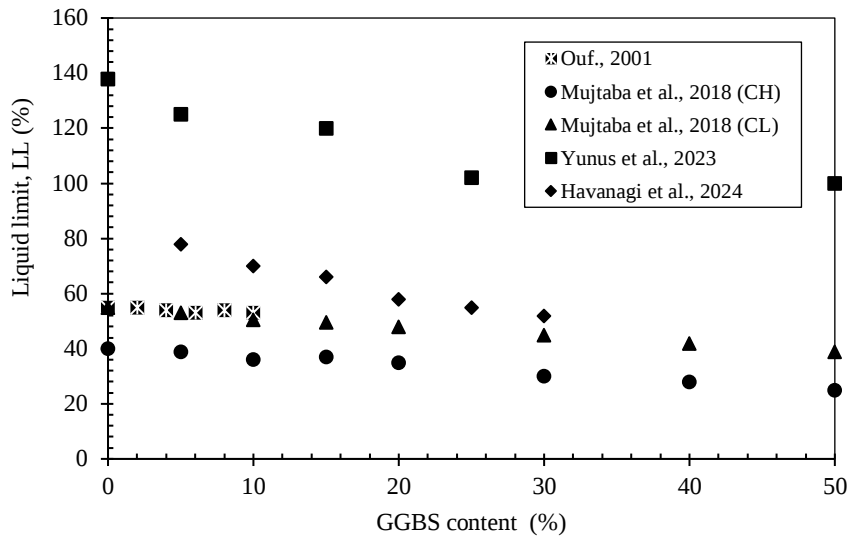


Figure 17: The effect of GGBS on LL of soil.

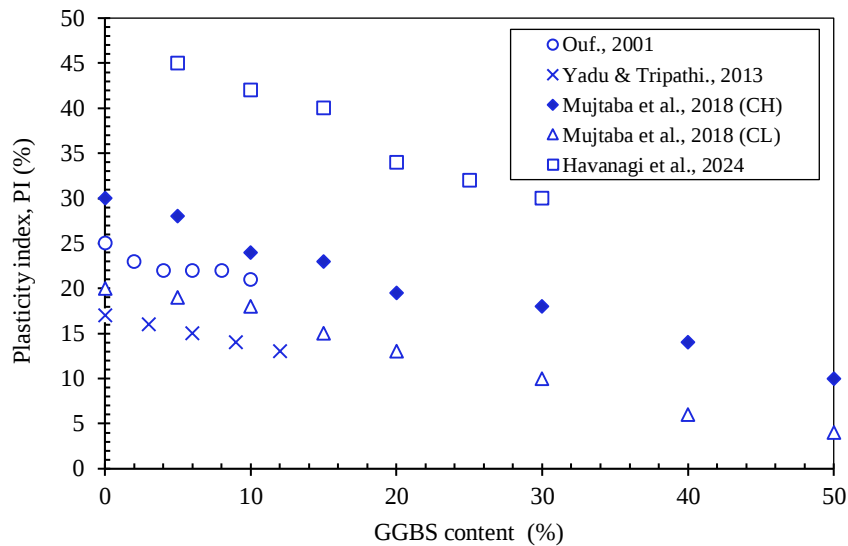


Figure 18: The effect of GGBS on PI of soil.

Previous results have demonstrated the varied and diverse effectiveness of using various wastes in soil improvement. However, most studies focus primarily on demonstrating improvements in geotechnical properties after the addition of various materials, without adequately explaining the observed variations in the behavior of these materials in other soil types. It is important to note that dealing with one type of soil may yield different results than others. For example, soil preparation through crushing and sieving may lead to discrepancies in previous results. Therefore, it is essential to develop a standardized methodology that clearly demonstrates how the use of these wastes affects geotechnical properties in different soil types and at specific particles sizes. Furthermore, soils under different moisture conditions may yield different results and variations in their durability and behavior. Furthermore, no adequate and clear study has been presented on the use of these wastes in soil under various processing conditions, such as immersion in water, at room temperature, in an oven, or in a microwave, based on the practical application of these mixtures. Moreover, relying heavily on laboratory results without actual field testing leaves a gap between theoretical and

practical application, as environmental conditions can significantly influence laboratory results.

Determining the effective percentages of each waste material in soil is crucial for future practical applications. Therefore, a complete range of replacements (0-100%) in soil need to be studied under various conditions (water content, curing method and period). While some research results have proposed the use of some of these materials in sustainable engineering applications, but the availability, processing, transportation and design costs of these materials were not emphasized. Regarding the environmental aspect, most of the results were ignored or only superficially addressed. There has been no real assessment of the safety of these waste materials when used in the field, particularly BA and FA, because they contain heavy metals such as lead, arsenic, or chromium, which may behave differently under certain conditions. Environmental contamination or toxicity tests, such as TCLP, SPLP, or leachability tests, should also be considered.

III. CONCLUSION AND RECOMMENDATIONS

This review investigated the effectiveness of various waste materials in stabilizing soil properties and identified the optimum levels for each. BA demonstrated the best performance at 50% combined with 12% lime, which improved CBR, pH, and plasticity values. FA showed high effectiveness at 25-30% content, improving various soil properties. RHA mixed with lime or cement at 10-15% significantly improved q_u and moisture content. CHA at 15-20% content significantly enhanced soil strength and reduced swelling. Furthermore, WA was most effective at 6-10% content, leading to substantial improvements in both CBR and q_u values. GGBS also contributed to enhanced strength and reduced swelling at 25-30% content. These improvements can be attributed to pozzolanic reactions, where the silica and alumina in the soil additives react with calcium and other soil materials to form strong cementitious compounds such as C-S-H and C-A-H, resulting in sustainable soil strengthening.

In the future, geotechnical researchers seeking to utilize sustainable and environmentally friendly materials for soil stabilization should focus on FA, RHA, and GGBS due to their high pozzolanic reactivity and continuous improvement in soil strength and durability. These materials are highly effective for reinforcing subgrade and pavement layers. Additionally, BA used up to 50% and CHA at 15-20% show great promise as sustainable stabilizers for improving soil strength and reducing plasticity, especially when mixed with lime or gypsum. Mixing these ashes with alkaline activators such as sodium silicate, bio-enzymes, or nano-silica can further accelerate and enhance pozzolanic reactions, improve bonding with soil particles, and form strong composites. Meanwhile, incorporating natural fibers like coconut or jute can enhance tensile strength and improve soil cracking resistance. It is strongly recommended that further exploration of soil stabilization compounds using industrial by-products and emerging environmentally friendly binders is undertaken, thus achieving an environmentally friendly alternative that achieves high soil performance and reduces environmental impact. The use of these wastes in real-world engineering applications is both important and effective. For instance, they can enhance 3D- soil printing, thereby facilitating the construction of earthen buildings. Additionally, it is possible to investigate the impact of some of these waste materials on the properties of various building materials, such as their use in the manufacture of blocks or building stones.

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DECLARATION OF INTEREST

The PI have no conflicts of interest to declare. All co-author (PI) have observed and affirmed the contents of the paper and there is no financial interest to report.

Waleed Zaid (PI): Conceptualization, Data curation, Visualization, writing original draft, methodology, investigation, formal analysis, validation, supervision,

project administration, funding acquisition, resources, software, writing, review and editing.

DATA AVAILABILITY

The datasets generated analyzed during this present study are available from the corresponding author upon request.

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ABBREVIATIONS

BA	Bottom ash
FA	Fly ash
RHA	Rusk waste ash
CHA	Coffee husk ash
WSA	Wood sawdust ash
GGBS	Ground granulated blast furnace slag
CH	High plasticity clay
CL	Low plasticity clay
MH	High plasticity silt
BCS	Black cotton soil
SC	Clayey sand
OL	Low plasticity organic
CI	Clay of intermediate plasticity
RCS	Red coffee soil
CL-ML	Low plasticity clay-silt
G	Gravel soil
ES	Expansive soil
OS	Organic soil
LS	Lateritic soil
SP	Poor sand
BT	Bentonite clay
UCS	Unconfined compressive strength test
q_u	Unconfined compressive strength
CBR	California bearing ratio
γ_{max}	Maximum dry density
w_{opt}	Optimum moisture content
k	Coefficient of permeability
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
SL	Shrinkage limit
Gs	Specific gravity
Su	Undrained shear strength
C	Cohesion
ϕ	Internal angle of friction
Cs	Swelling index
Cc	Compression index
FSI	Free swell index
e_0	Initial void ratio

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APPENDIX A

Supplementary Tables. This appendix contains the supplementary tables that support the findings discussed in this present study.